

Six-field two-fluid ELM simulations with Landau-Fluid closures



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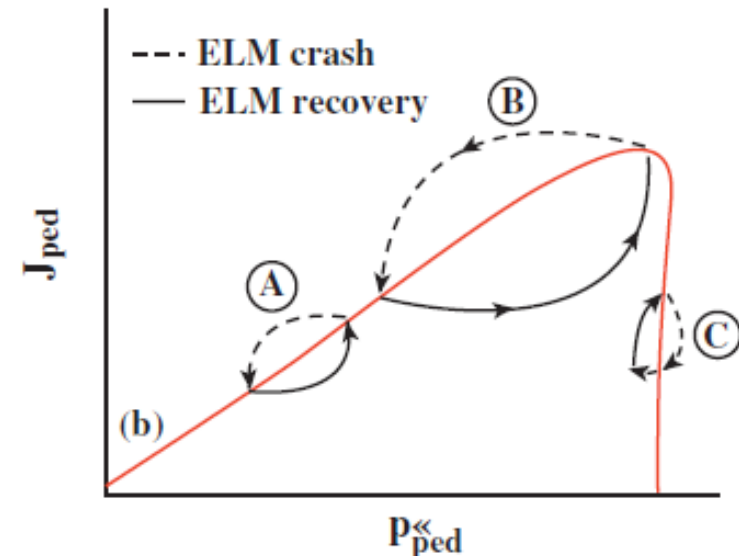
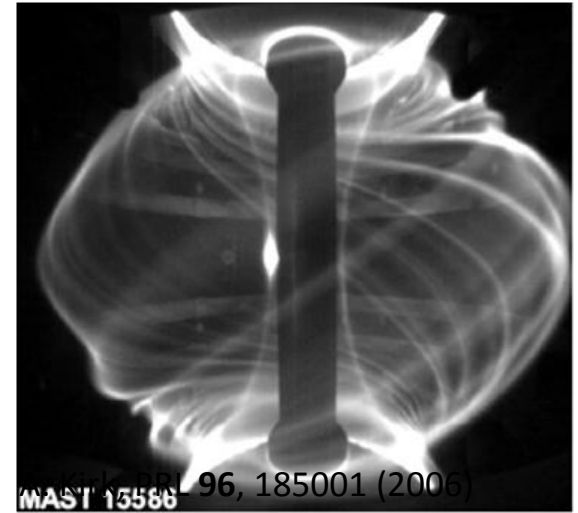
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Outline

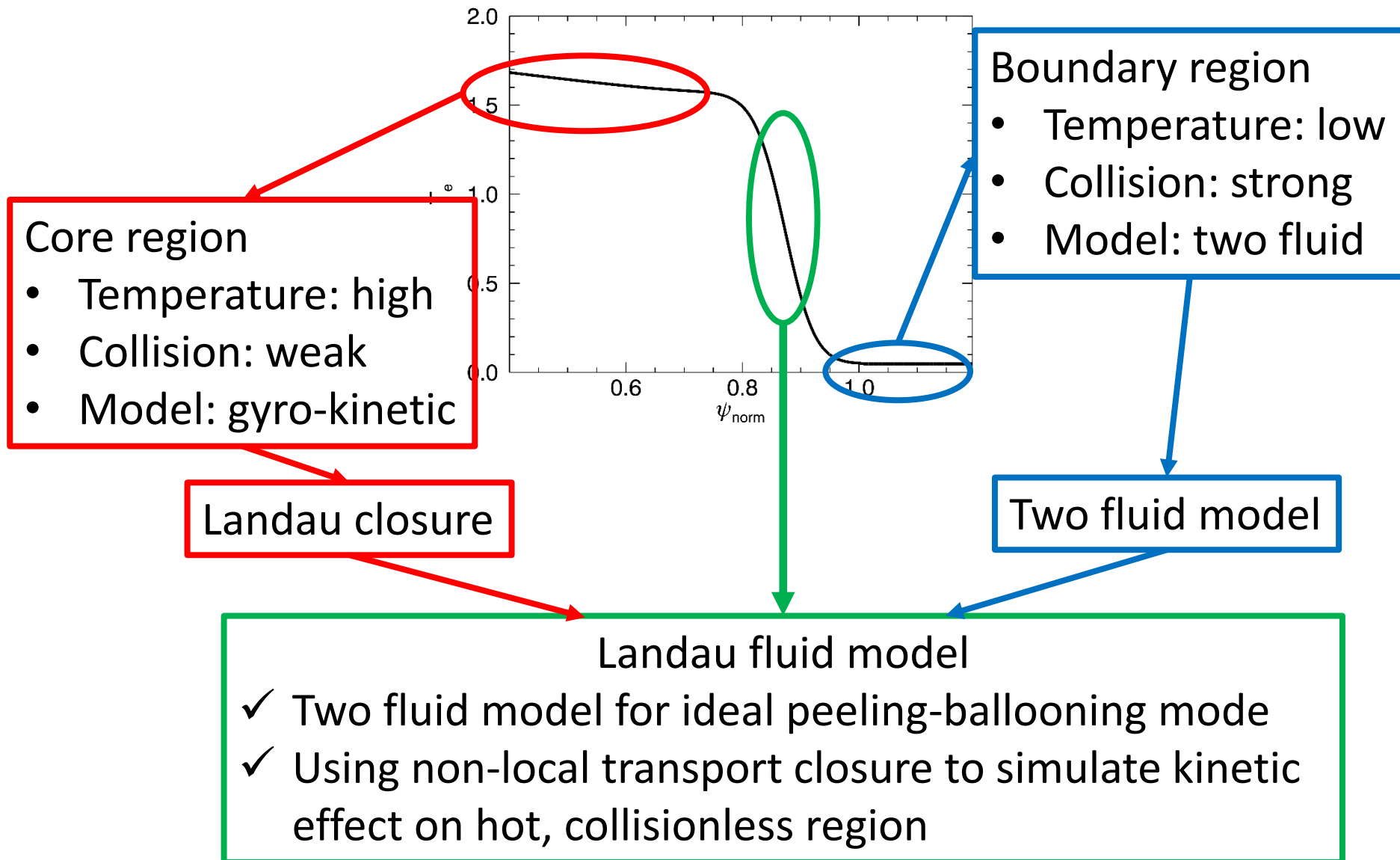
1. Introduction
2. Physics Model
3. Simulation Result
 - 1) Effect of different parallel heat flux closures
 - 2) L_n/L_t scan
 - 3) Effect of thermal force
4. Summary

Background

- H-mode
 - Better power confinement for plasmas
 - Edge transport barrier and pedestal region
- ELMs
 - Periodic MHD events at H-mode pedestal;
 - Damage to PFC;
 - Affect confinement;
- Peeling-ballooning model
 - Driven by combination of high pressure gradient and current
 - Different linear instabilities, different types of ELMs.



Landau fluid model can fill the gap between hot and cold boundary plasma



6-field includes the effect of thermal conductivity and temperature profile

Model	Variables	Physics
3-field	ϖ, A_{\parallel}, P	Peeling-ballooning model
6-field	$\varpi, A_{\parallel}, n_i, V_{\parallel i}, T_i, T_e$	+Thermal conductivity

- 3-field:
 - Only peeling-ballooning model
- 6-field:
 - Thermal conductivity
 - Landau closure: collisionless wave-particle resonances
 - Flux limited heat flux: collisional transport and flux streaming
 - Effect of temperature profile $\rightarrow \eta_i = L_n/L_T$ scan

6-field two fluid model with parallel heat flux

Vorticity:

$$\begin{aligned} \frac{\partial}{\partial t} \varpi = & - \left(\frac{1}{B_0} b \times \nabla_{\perp} \phi + V_{\parallel i} b \right) \cdot \nabla \varpi + B^2 \nabla_{\parallel} \left(\frac{J_{\parallel}}{B} \right) + 2b \times \kappa \cdot \nabla P \\ & - \frac{1}{2\Omega_i} \left[\frac{1}{B} b \times \nabla P_i \cdot \nabla (\nabla_{\perp}^2 \phi) - Z_i e B b \times \nabla n_i \cdot \nabla \left(\frac{\nabla_{\perp}^2 \phi}{B} \right)^2 \right] \\ & + \frac{1}{2\Omega_i} \left[\frac{1}{B} b \times \nabla \phi \cdot \nabla (\nabla_{\perp}^2 P_i) - \nabla_{\perp}^2 \left(\frac{1}{B} b \times \nabla \phi \cdot \nabla P_i \right) \right] + \mu_{\parallel i} \nabla_{\parallel 0}^2 \varpi \end{aligned}$$

Ion density:

$$\frac{\partial}{\partial t} n_i = - \left(\frac{1}{B_0} b \times \nabla_{\perp} \phi + V_{\parallel i} b \right) \cdot \nabla n_i - \frac{2n_i}{B} b \times \kappa \cdot \nabla \phi - \frac{2}{Z_i e B} b \times \kappa \cdot \nabla P - n_i B \nabla_{\parallel} \left(\frac{V_{\parallel i}}{B} \right)$$

Ion parallel velocity:

$$\frac{\partial}{\partial t} V_{\parallel i} = - \left(\frac{1}{B_0} b \times \nabla_{\perp} \phi \right) \cdot \nabla n_i - \frac{1}{m_i n_i} b \cdot \nabla P$$

Ohm's law:

$$\frac{\partial}{\partial t} A_{\parallel} = - \nabla_{\parallel} \phi + \frac{\eta}{\mu_0} \nabla_{\perp}^2 A_{\parallel} + \frac{1}{e n_e} \nabla_{\parallel} P_e + \frac{\alpha_e k_B}{e} \nabla_{\parallel} T_e - \frac{\eta_H}{\mu_0} \nabla_{\perp}^4 A_{\parallel}$$

Thermal force

Ion temperature:

$$\begin{aligned} \frac{\partial}{\partial t} T_i = & - \frac{2}{3} T_i \left[\left(\frac{2}{B} b \times \kappa \right) \cdot \left(\nabla \phi + \frac{1}{Z_i e n_i} \nabla P_i + \frac{5k_B}{2Z_i e} \nabla T_i \right) + B \nabla_{\parallel} \left(\frac{V_{\parallel i}}{B} \right) \right] \\ & - \left(\frac{1}{B_0} b \times \nabla_{\perp} \phi + V_{\parallel i} b \right) \cdot \nabla T_i - \frac{2}{3n_i k_B} \nabla_{\parallel} q_i + \frac{2m_e}{m_i} \frac{Z_i}{\tau_e} (T_e - T_i) \end{aligned}$$

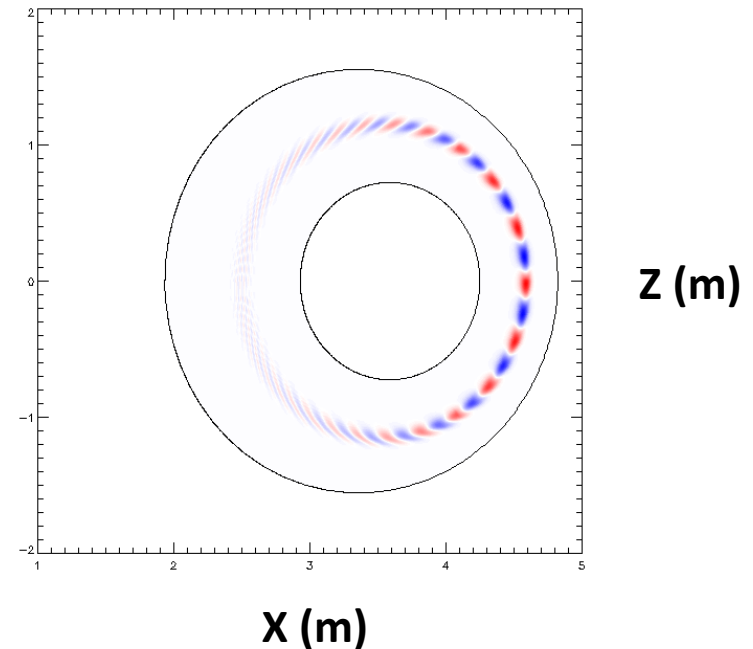
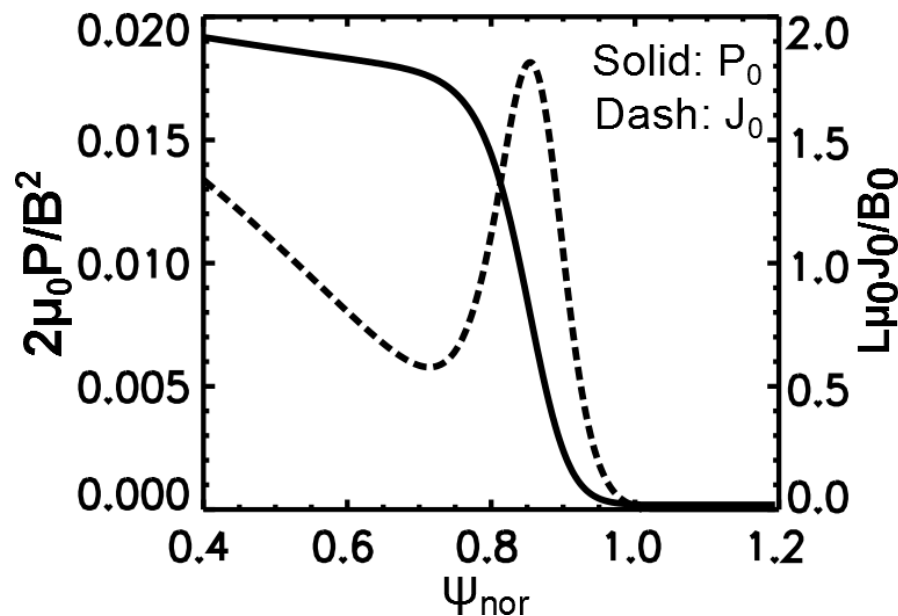
Parallel heat flux

Electron temperature:

$$\begin{aligned} \frac{\partial}{\partial t} T_e = & - \frac{2}{3} T_e \left[\left(\frac{2}{B} b \times \kappa \right) \cdot \left(\nabla \phi + \frac{1}{Z_i e n_i} \nabla P_e + \frac{5k_B}{2Z_i e} \nabla T_e \right) + B \nabla_{\parallel} \left(\frac{V_{\parallel i}}{B} \right) \right] \\ & - \left(\frac{1}{B_0} b \times \nabla_{\perp} \phi + V_{\parallel i} b \right) \cdot \nabla T_e - \frac{2}{3n_i k_B} \nabla_{\parallel} q_e - \frac{2m_e}{m_i} \frac{Z_i}{\tau_e} (T_e - T_i) \end{aligned}$$

Different balance pressure profile

- Simulations are based on the shifted circular cross-section toroidal equilibria (cbm18_den6) generated by the TOQ code*.



* X.Q. Xu and R.H. Cohen, *Contrib. Plasma Phys.* 38, 158 (1998)

- Umansky, Xu, Dudson, et al., , *Comp. Phys. Comm.* V. 180 , 887-903 (2008).
- Dudson, Umansky, Xu et al., *Comp. Phys. Comm.* V.180 (2009) 1467.

Classical thermal conductivities and Landau damping closure

Landau damping closure

$$q_{\parallel i} = -n_0 \sqrt{\frac{8}{\pi}} v_{T\parallel i} \frac{ik_{\parallel} k_B T_i}{|k_{\parallel}|}$$
$$q_{\parallel e} = -n_0 \sqrt{\frac{8}{\pi}} v_{T\parallel e} \frac{ik_{\parallel} k_B T_e}{|k_{\parallel}|}$$

✓ Non-local thermal transport

classical thermal conductivities

$$q_{\parallel i} = -\kappa_{\parallel i} \nabla_{\parallel} k_B T_i$$
$$q_{\parallel e} = -\kappa_{\parallel e} \nabla_{\parallel} k_B T_e$$

Where

$$\kappa_{\parallel i} = \left(\kappa_{\parallel i}^{SH^{-1}} + \kappa_{\parallel i}^{FS^{-1}} \right)^{-1}$$
$$\kappa_{\parallel e} = \left(\kappa_{\parallel e}^{SH^{-1}} + \kappa_{\parallel e}^{FS^{-1}} \right)^{-1}$$

$$\kappa_{\parallel i} = 3.9 n_i v_{th,i}^2 / \nu_i$$
$$\kappa_{\parallel e} = 3.2 n_e v_{th,e}^2 / \nu_e$$

Spitzer-Harm

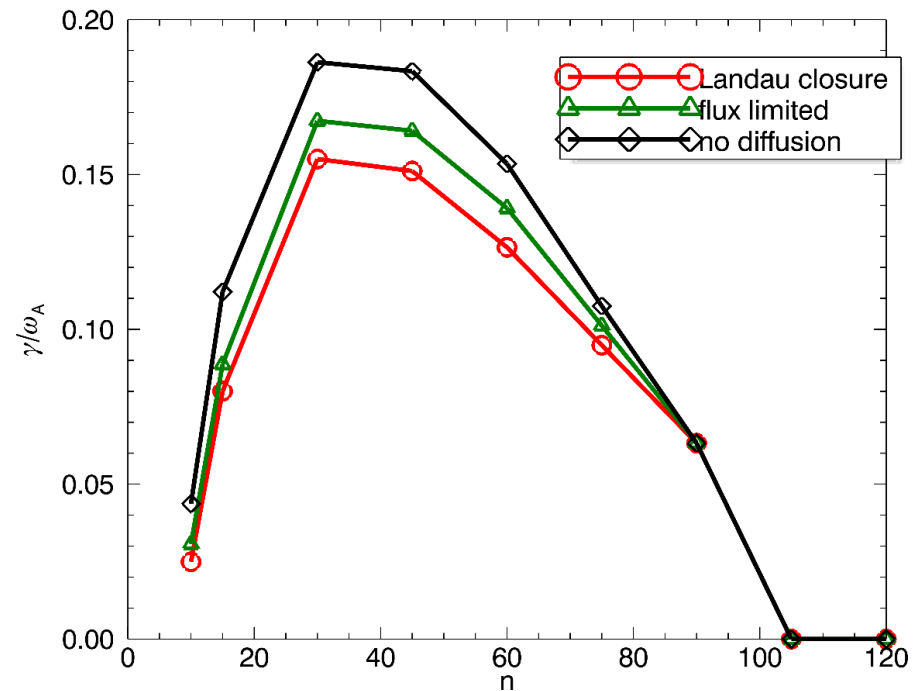
$$\kappa_{\parallel j}^{FS} = n_j v_{th,j} q R_0$$

Flux streaming

✓ Classical heat flux

Landau closure has more damping effect on linear growth rate, but not very strong

- Both Landau closure and flux limited thermal conductivity has stabilizing effect on peeling-ballooning modes;
- Landau closure has stronger stabilizing effect;
- Thermal conductivity doesn't change the unstable island of modes.



Why the stabilizing effect from local/nonlocal parallel thermal conductive is not that strong?

Landau Damping and flux limited conductivity should have no effect on rational surface

- For ideal ballooning mode, dispersion relation is

$$\omega(\omega - i\chi_{\parallel}k_{\parallel}^2) + \gamma_I^2 = 0$$

- We get growth rate

$$\gamma = \frac{1}{2} \left(-\chi_{\parallel}k_{\parallel}^2 + \sqrt{\chi_{\parallel}^2k_{\parallel}^4 + 4\gamma_i^2} \right)$$

Parallel conductivity effect

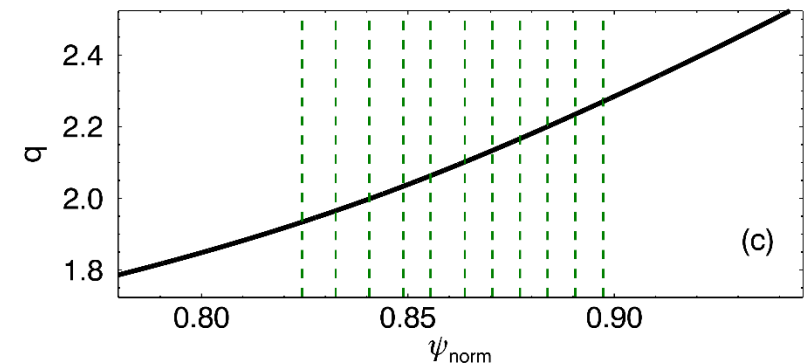
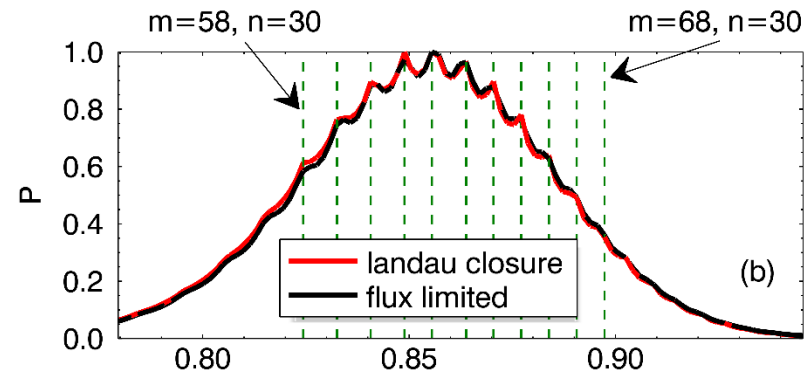
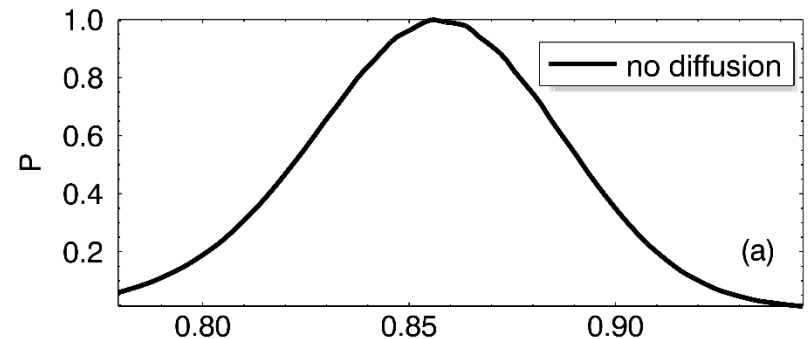
- Parallel conductivity has a stabilizing effect on peeling ballooning mode
- **Parallel conductivity should have no effect on rational surface which $k_{\parallel} = 0 \rightarrow$ Radial structure**

Our simulations show consistent radial structure with theoretic expectation!

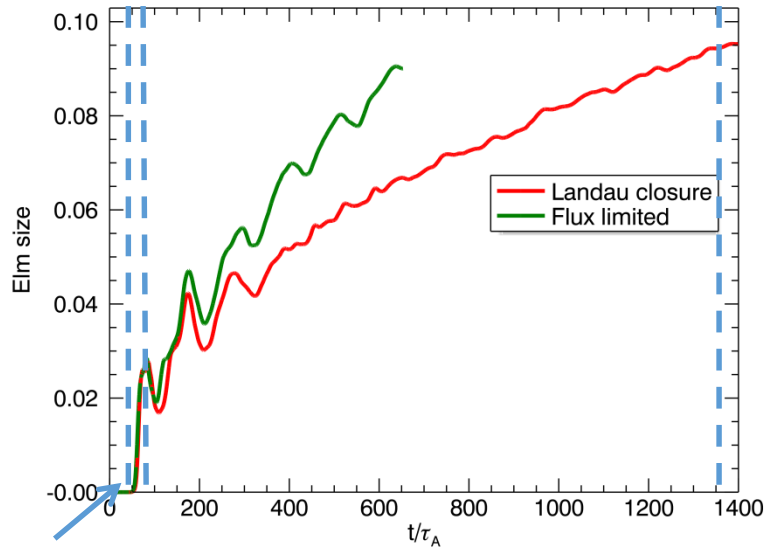
- Radial mode structure
 - Without parallel diffusion: smooth;
 - With Landau damping for flux limited thermal conductivity: peaked at rational surface.

	Rational surface	Irrational surface
Instability	Strong	Weak
Parallel damping	Weak	Strong

- The mismatch between instability and parallel diffusion reduces the damping effect on peeling ballooning modes.



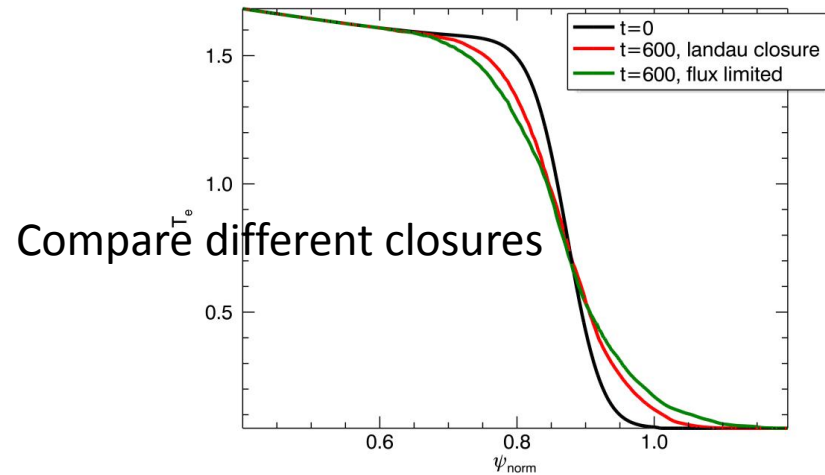
Landau damping leads to smaller ELM size in nonlinear simulations than flux limited expression



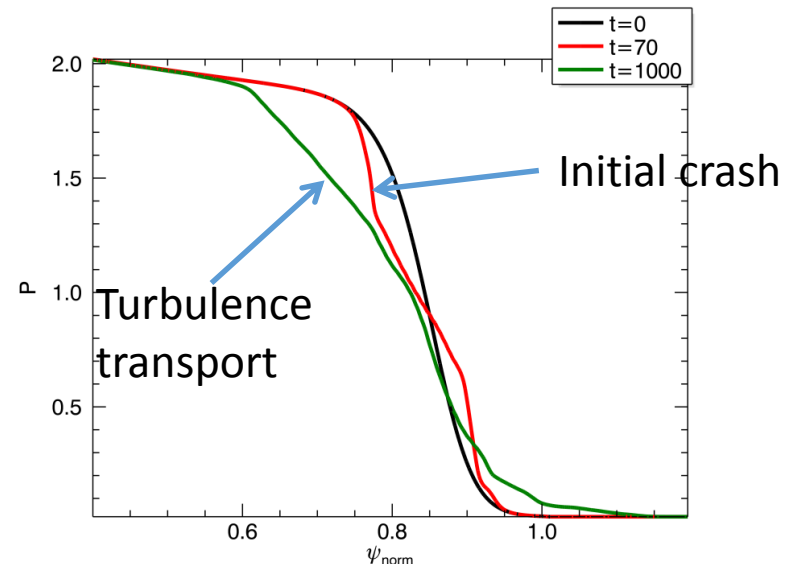
Elm crash

Turbulence
transport

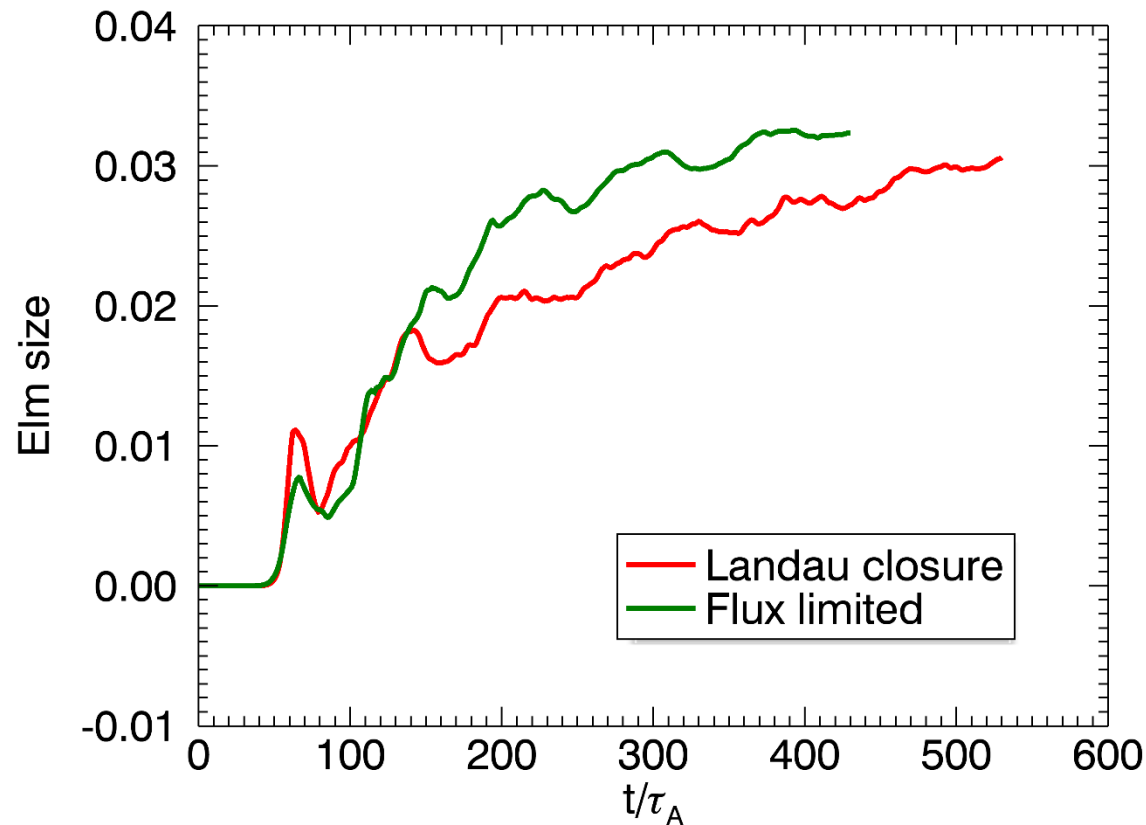
- Nonlinear result is similar as linear result;
- Landau damping closure has more damping effect on the turbulence transport phase of elm crash;
- Elm size with Landau closure is smaller than Elm size with flux limited heat flux;



Compare different closures

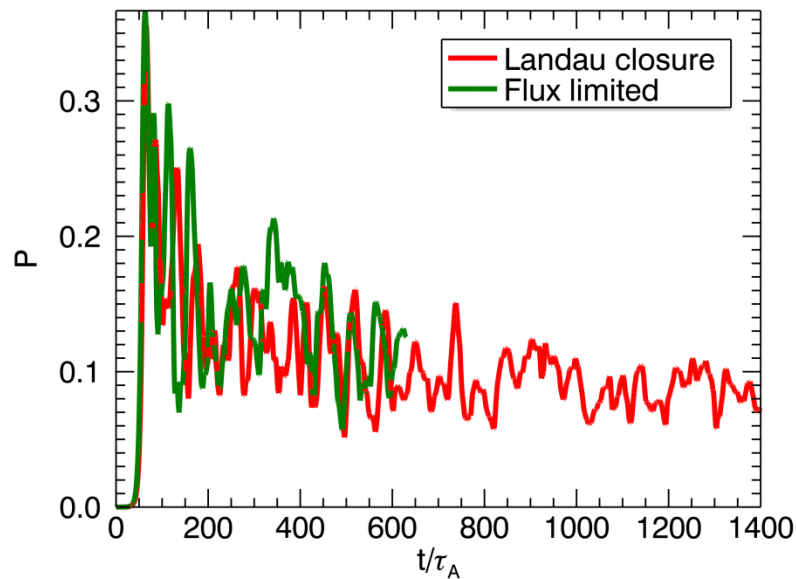


For larger $L_n/L_t=4$, ELMs become saturated faster

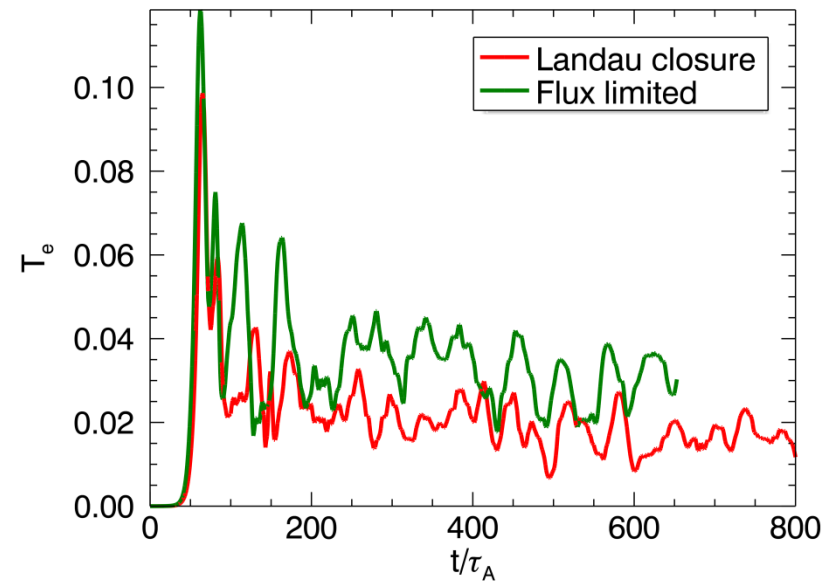


- Elm size soon becomes saturate for larger L_n/L_t ;
- With Landau closure, we get smaller ELM size.

Landau closure has more damping effect on temperature disturbance than pressure



Pressure disturbance is similar



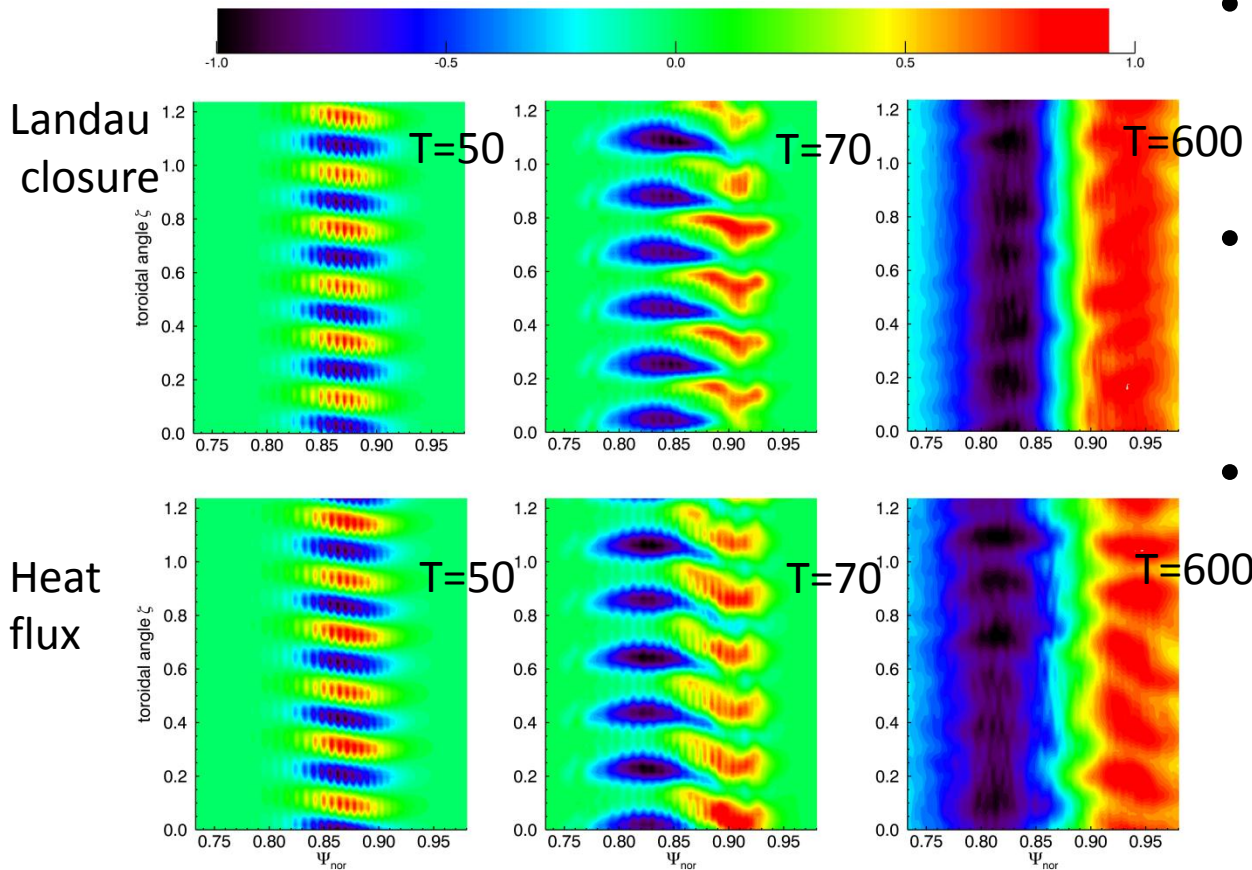
Temperature disturbance with Landau closure is small than the case with flux limited heat flux

Effect on rational surface during linear phase

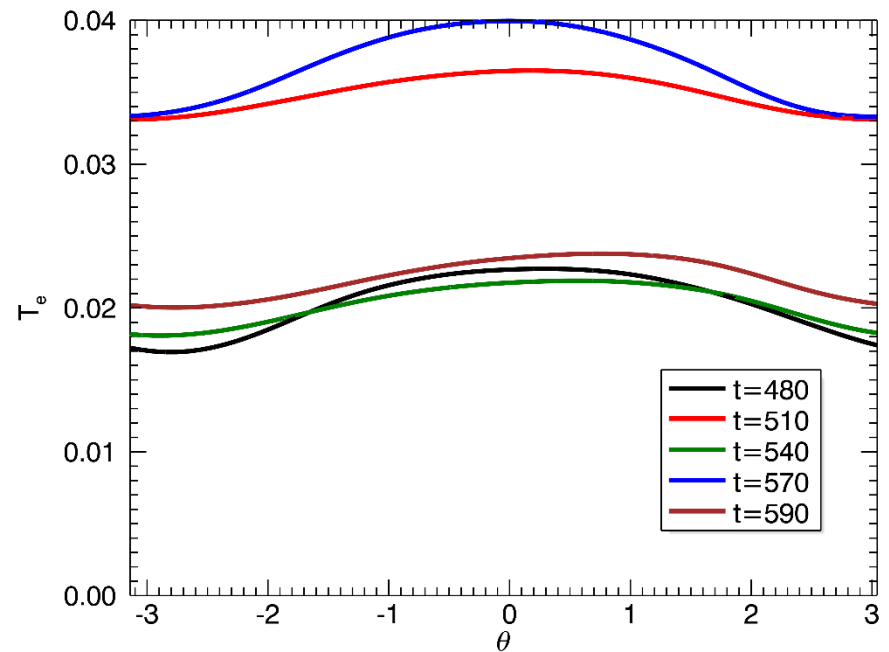
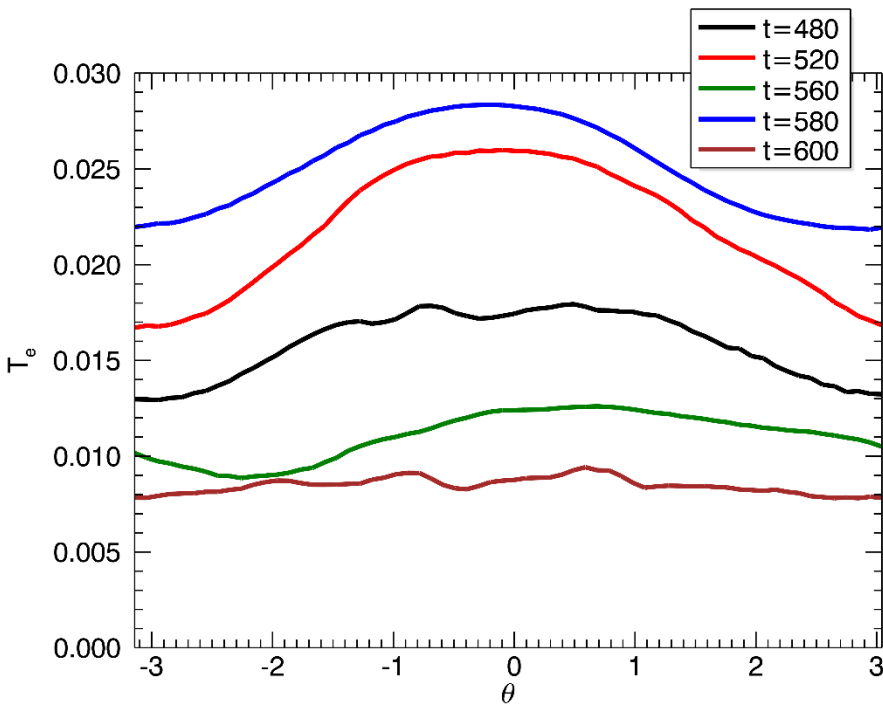
- Electron temperature contour of nonlinear run

- Parallel heat flux has no effect on rational surface

- Trace of rational surface disappear in the turbulence state



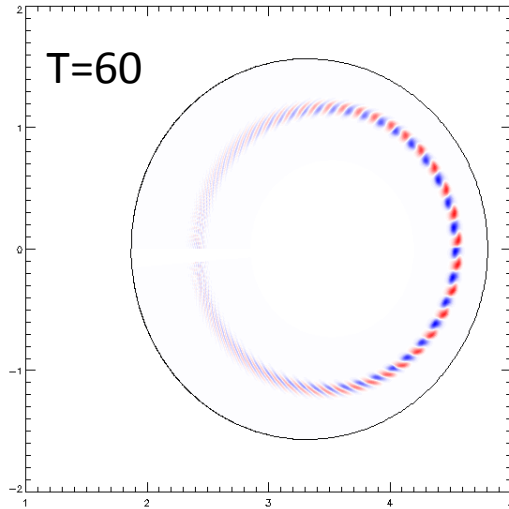
Poloidal temperature oscillating during turbulence transport phase



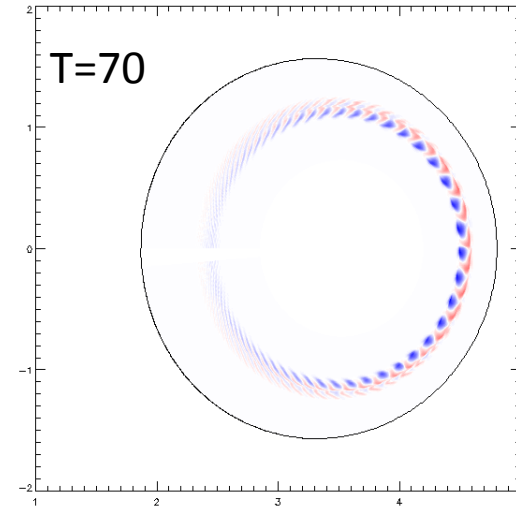
Landau closure makes poloidal temperature profile more flat

Mode structure on Cylindrical coordinates

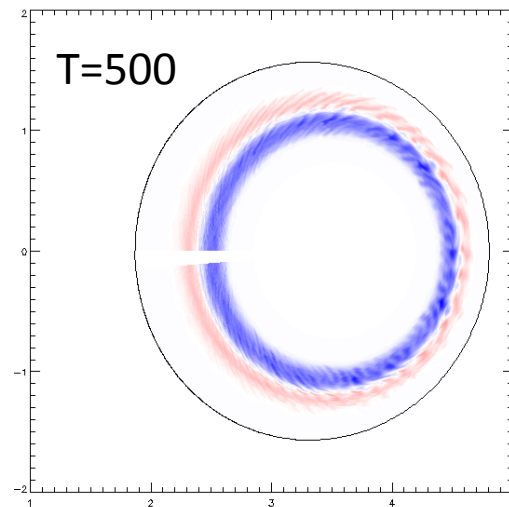
Before
crash



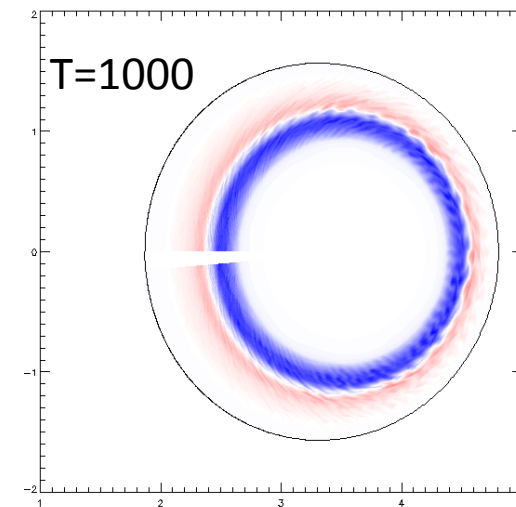
After
crash



Turbulence
state



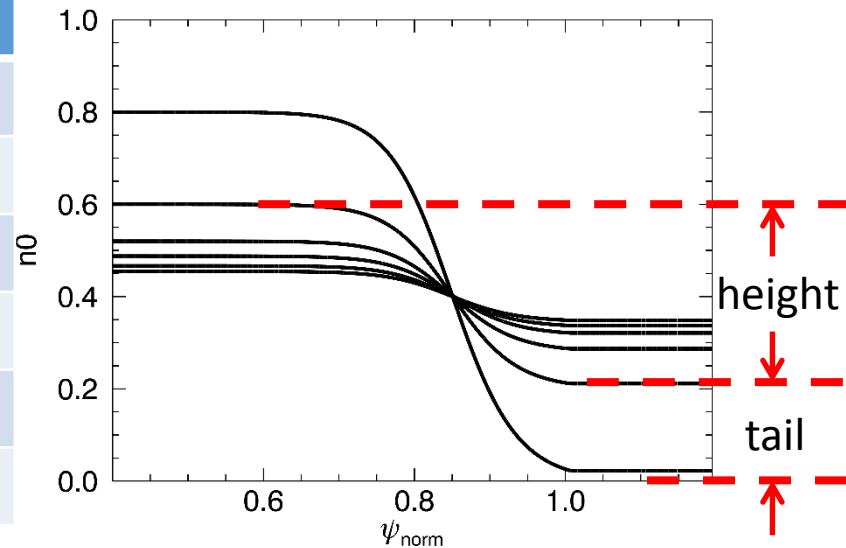
Turbulence
state



Different L_n/L_t

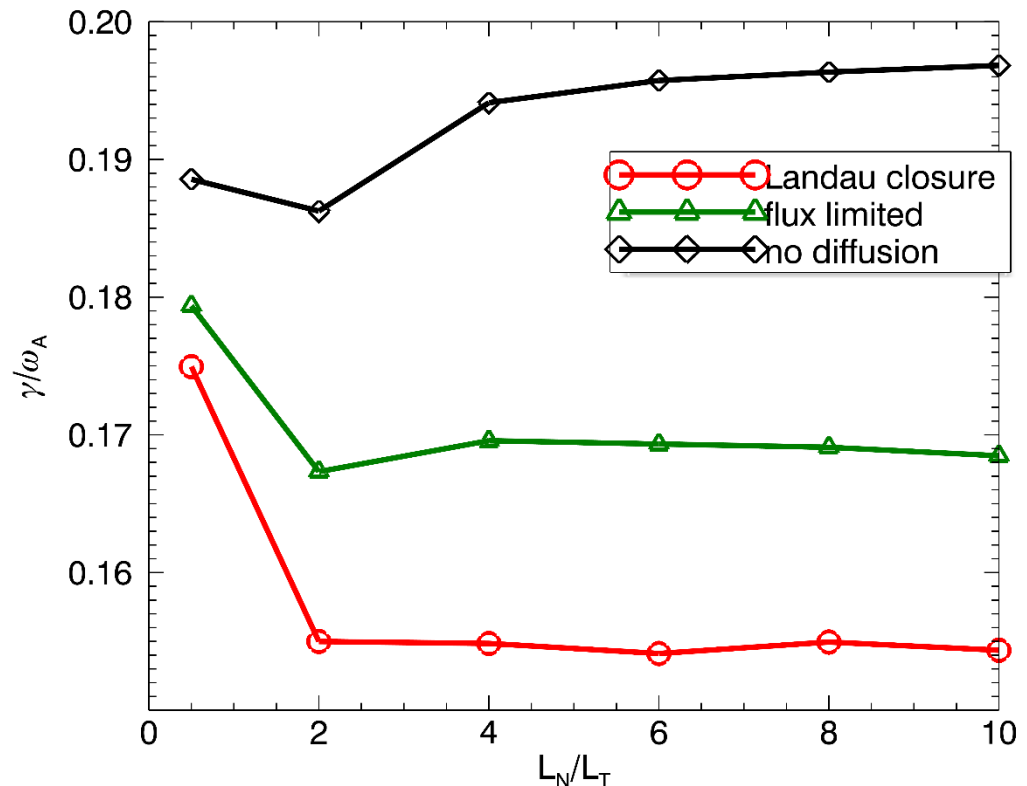
- Keep the same pressure profile, change density and temperature;
- L_n/L_t scan:

L_n/L_t	Height	tail
0.5	0.800	0.000
2	0.400	0.200
4	0.240	0.280
6	0.171	0.316
8	0.133	0.333
10	0.109	0.345



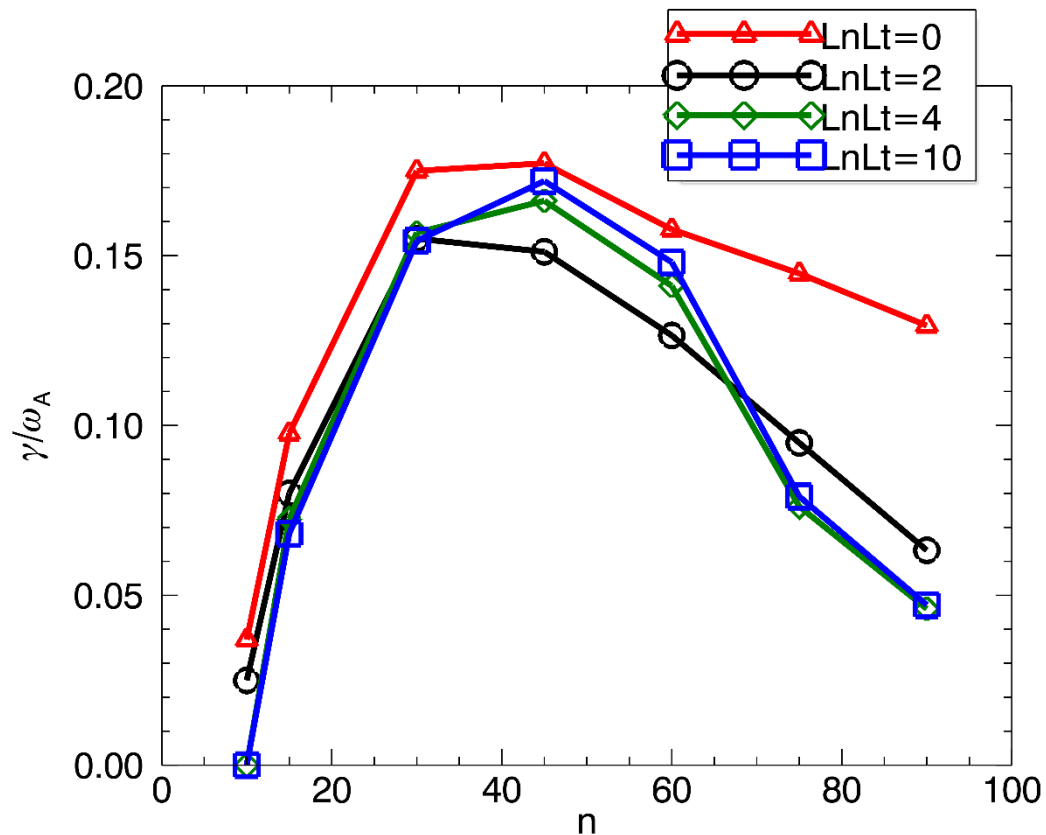
Damping effect is strong when L_n/L_T is large

- Keep pressure profile and local density and temperature profile fixed, change L_n/L_T
- L_n/L_T has small effect on peeling ballooning mode
- Parallel conductivity has small effect when L_n/L_T is small



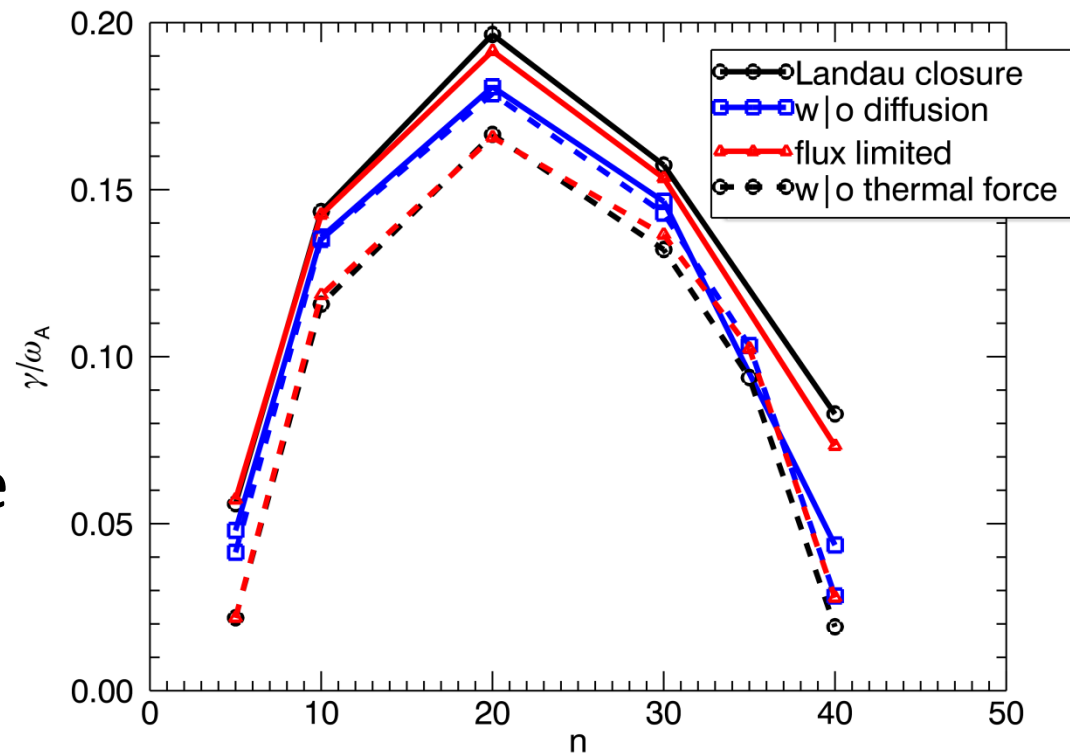
L_n/L_T has little effect on growth rate spectrum

- L_n/L_T has small effect on the growth rate and spectrum;
- Small effect from diamagnetic term because of different density gradient profile.



Thermal force, when coupled with parallel heat flux, can destabilizes modes

- **With Landau closure or flux limited diffusion:** Thermal force has an unstable effect on modes;
- **Without parallel diffusion:** Thermal force has small effect on the linear growth rate of modes.



Summary

- Parallel conductivity term has stabilize effect on peeling-ballooning mode and can reduce elm size;
- Landau closure has more damping effect on the linear growth rate of peeling-ballooning mode;
- With Landau closure, temperature disturbance is small on the turbulence transport phase of elm crash.

